Switched-Capacitor Filters

by Anton Kruger

Introduction

The circuit in Figure 1 consists of two capacitors and two switches controlled by two non-overlapping clocks, Φ1 and Φ2. When Φ1 is high, S1 closes while S2 is open. When Φ1 goes low, S1 closes. Then after a short delay, Φ2 goes high, and S2 closes. This cycle repeats and S1 and S2 close and open alternatively, but they are never closed at the same time. The clock frequency is 10 kHz. The input to the circuit is the sum of a 5V, 75 Hz sine and a 1V, 2 kHz sine. The output from the circuit is shown in Figure 2.

For comparison, the output from passing the signal through a first order RC filter with a 500 Hz 3-dB bandwidth is shown, as well. Except for the small stair-casing, the output from the circuit is very close to the output from the RC filter. What is going on here?

The circuit in Figure 1 is what is known as a switched-capacitor filter. When Φ1 is high, S1 is closed and capacitor C_{sc} charges to v_1. Then it opens and C_{sc}c retains the charge and voltage. After a short delay, S2 closes and the capacitor charges to v_2. Now

$$q = CV$$

so that the change in charge is

$$\Delta q = C_{sc}(v_1 - v_2)$$

Recall that current is defined as the charge per unit time transferred, and assume that the period T of the cycle: S1 closes, S1 opens, S2 closes, S2 opens ... is short enough so that the voltages v_1 and v_2 don't change appreciably. It is clear then that the charge transferred by the switched-capacitor can be viewed as a current given by:

$$i = \frac{\Delta q}{T} = \frac{C_{sc}(v_1 - v_2)}{T}$$

From Ohm's Law we can write:

$$R_{sc} = \frac{v_1 - v_2}{i} = \frac{T}{C_{sc}} = \frac{1}{f_{clk} C_{sc}}$$

where $1/T = f_{clk}$ is the clock frequency. Thus, the switched-capacitor acts like a resistor with value given above, in that it will result in the same charge transfer per unit time as a conventional resistor of the same value. With this in mind, we can redraw Figure 1 to reveal its function as an RC lowpass filter, as shown in Figure 3. Plugging in the values shows that the switched-capacitor resistor has a value

$$R_{sc} = \frac{1}{f_s C_{sc}} = \frac{1}{10 \times 10^3 \times 20 \times 10^{-12}} = 5\ \text{M}\Omega$$

The 3-dB or corner frequency of the filter is:

$$f = \frac{1}{2\pi\ R_{sc} C_f} = \frac{1}{2\pi \times 5 \times 10^6 \times 64 \times 10^{-12}} = 497 \approx 500\ \text{Hz}$$

Of course, the current flowing through the switched capacitor resistor is not continuous as with a conventional resistor, which explains the stair-casing in the output. Except for this artifact, however, we have succeeded in building an RC filter without any (conventional) resistor. In practice, the switches S1 and S2 are transistors.

While this may be an intriguing concept, it is valid to question why one would go to all the trouble and expense of overlapping clocks and voltage-controlled switches to replace a simple RC filter. One reason may be that the switched-capacitor resistor is a function of the clock frequency, so that one can change the resistance by varying the clock frequency. In other words, it is an electrically controllable resistor. However, there are easier and cheaper ways of accomplishing this.

To understand why switched-capacitors are useful, one has to understand a few facts about IC manufacturing. The first thing is transistors, and transistors use switches that are cheap and easy to manufacture. Small-value capacitors are also easily manufactured. Small-value resistors are manufactured using strips of the IC chip. This is good for up to a few hundred ohm, but larger values become problematic because they require so much chip real-estate. Chip designers and manufacturers would much rather use several transistors to avoid using one large-value resistor, since it is more cost-effective. This explains why, in a typical IC, the number of transistors outnumber the other components. This is opposite to traditional discrete electronics where transistors are expensive, and resistors and capacitors are cheap.

Transistor-centric designs can be and are very effective in a great many instances. However, there are times where large-value resistors are needed. One example is filters with large time constants. To achieve a large time constant, one needs either a large resistance, a large capacitance, or both. As we have discussed, large capacitances – and especially large resistances – are undesirable in IC designs. Enter the switched capacitor – the circuit in Figure 1 implements a 5MΩ resistor using two switches and a capacitor, but costs next to nothing in an IC.

While the main advantage of switched-capacitors is that they provide a means of implementing large-value resistors, another advantage is that they are electrically-controllable. An additional advantage becomes clear if one considers the expression for the 3-dB bandwidth of the low-pass filter in Figure 1:

$$f_{3dB} = \frac{1}{2\pi\ R_{sc} C_f} = \frac{1}{2\pi\left(\frac{1}{f_{clk} C_{sc}}\right) C_f} = \frac{f_s C_{sc}}{2\pi C_f} \quad (1)$$

The corner frequency is a function of the ratio of two capacitances. This is perfect for an IC implementation where it is difficult to make values of individual components exact, but it is easy to control their ratio to within less than 1%.

Commercial Switched-Capacitor Filters

Commercial switched-capacitor filters are high-order active filters, rather than the simple first-order RC filter in Figure 1. However, the principles are the same – virtual resistances are created using a combination of switches and capacitors. Table 1 summarizes some of the ICs available. Packaging options include DIP and SO. Prices range from less than a dollar for the MF4, to $30.00 for the MAX260. Typically, cutoff frequencies can be adjusted over the range 0.1 Hz-40 kHz simply by changing the clock frequency.

Some of the filters in Table 1 are designated as "universal" while others are implicitly "dedicated." Universal filters provide the designer with the basic building blocks and he/she can configure it to form low-pass, notch, bandpass, etc., filters of various types: Butterworth, Bessel, and so on. Dedicated filters are preconfigured filters such as an eighth order lowpass Butterworth, or eighth order lowpass elliptic filter, and so on.

Clock-To-Corner Frequency Ratio

The clock frequency f_{clk} of the simple switched-capacitor filter in Figure 1 is 10 kHz, while the corner frequency is 500 Hz, so that there is a 20:1 ratio between clock and corner frequency. The ratio for commercial switched-capacitor filters is normally 50:1 or 100:1. In some filters, this ratio is fixed and the part number indicates the ratio. Thus, the MF4-50 part from National has a 50:1 ratio, while the MF4-100 part is an identical filter except that it has a 100:1 ratio. Other IC filters allow the user to select one of the two ratios. A high clock/corner frequency ratio reduces the stair-casing, but requires a higher clock frequency that may be undesirable from other circuit constraints.

Characteristics And Applications

The characteristics of a particu-

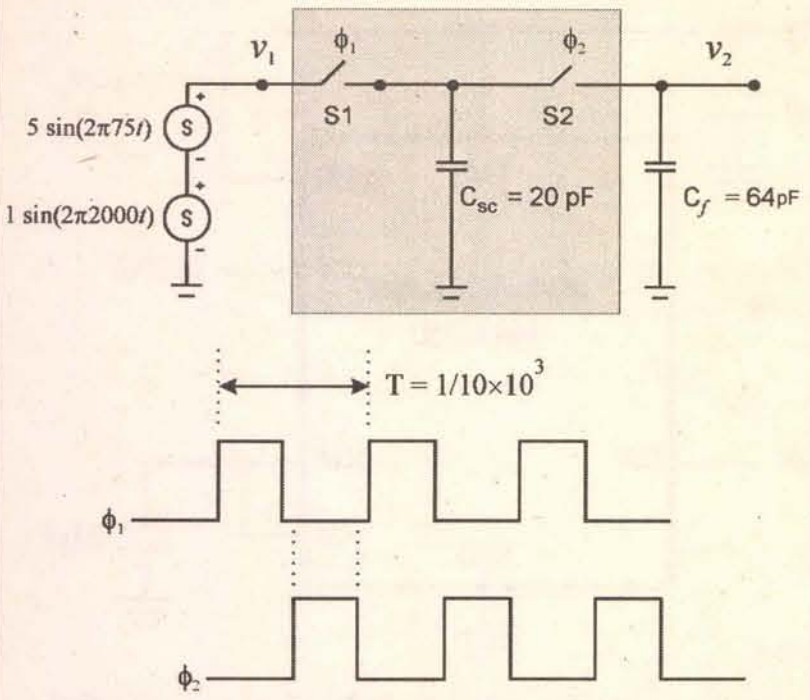

Figure 1. Switched-capacitor circuit. Voltage-controlled switches S1 and S2 are controlled by non-overlapping clocks Φ_1 and Φ_2 running at 10 kHz. When Φ_1 is high, S1 is closed and S2 is open. When Φ_2 is high, S2 is closed, and the switches are never closed at the same time.

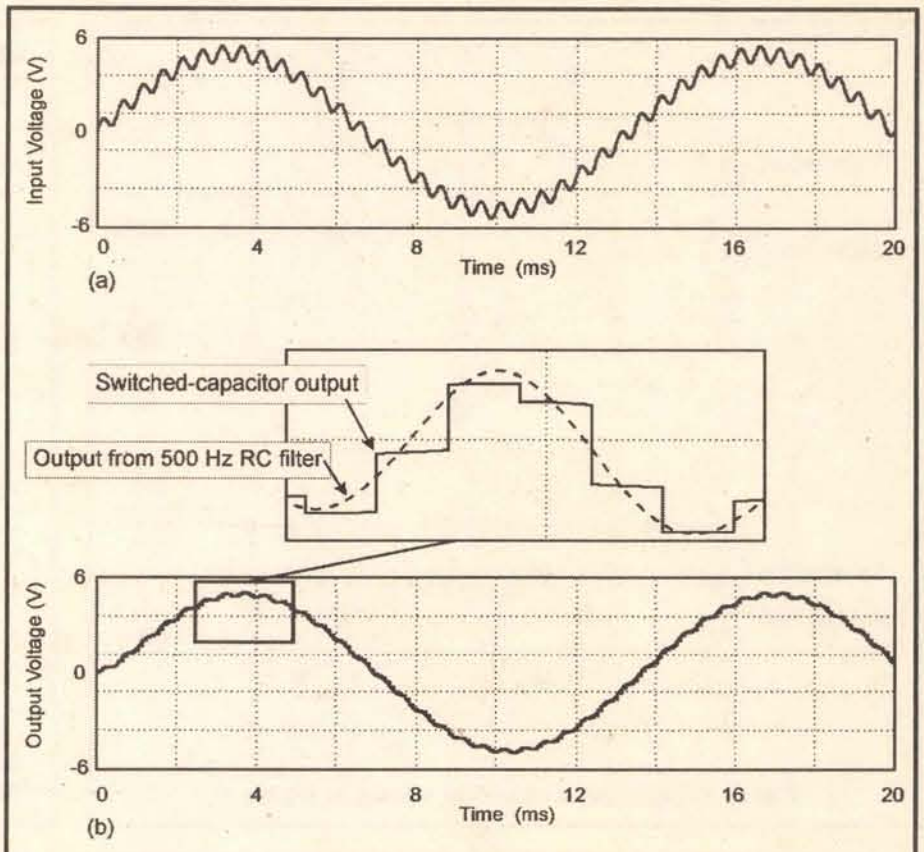

Figure 2. (a) Input to switched-capacitor circuit. (b) Output from circuit in Figure 1. For comparison, the output from a 500 Hz RC filter is shown, as well.

lar switched-capacitor filter obviously depend on the component, but all these filters share some general characteristics. First, the stair-casing in the output is inherent in the technique. It may come as a surprise, but this is, in many cases, not a problem. For example, switched-capacitor filters are often used in filtering the output from a DAC, possibly followed by a conventional analog filter. The stair-casing from the DAC will be much larger than that from the switched-capacitor filter. The idea is that the switched-capacitor filter provides the heavy-duty filtering, so that a relatively simple final analog filter will suffice.

In some instances, the bandwidth of the circuit that follows the switched-capacitor filter may be such that it removes the stair-casing, or the stair-casing may not be important. For example, if the output goes to a speaker with bandwidth of a few kHz, then stair-casing at 50 kHz may be irrelevant in many instances.

In any event, one can always easily reduce the stair-casing by following the switched-capacitor filter with a simple lowpass filter. The corner frequency of this filter is normally the switched-capacitor clock frequency, which is relatively high, and easy to filter out. Here is an instance where a high clock/corner frequency ratio may be an advantage.

Switched-capacitor filters exhibit excellent temperature stability, and a 10 ppm/°C temperature coefficient for the clock/corner frequency ratio is not unusual. This is a direct result of the fact that corner frequencies depend on the ratios of capacitances (see Equation 1), and variations in temperature tend to cancel out. This, and the fact that (for practical purposes) the corner frequency depends only on the clock frequency, is a tremendous advantage over conventional analog filters. Some conventional analog filter designs are quite sensitive to component variations, and it may be difficult and expensive to achieve the same performance.

Designing Switched-Capacitor Filters

Since the switched-capacitor filter is a sampled-data component, one has to be careful to avoid frequency aliasing or folding. Practically, this means one has to ensure that there are no significant frequency components in the input above the Nyquist frequency, which is $f_{clck}/2$. Another thing to watch out for is when the switched-capacitor filter is used to post-filter the output from an DAC. Here it is best to synchronize the filter clock to the DAC clock, otherwise beats between the two clocks may show up in the output. In some cases, a simple RC lowpass filter may be required.

Except for these few simple precautions, it is quite easy to use switched-capacitor filters. A design typically involves matching the specification of the filter with one of the dedicated switched-capacitor filters available, and supplying the appropriate clock signal.

As an example, the MAX7480 switched-capacitor filter requires a single +5V supply, two non-critical decoupling capacitors, and an external clock to implement an eighth order lowpass Butterworth filter with corner frequency adjustable

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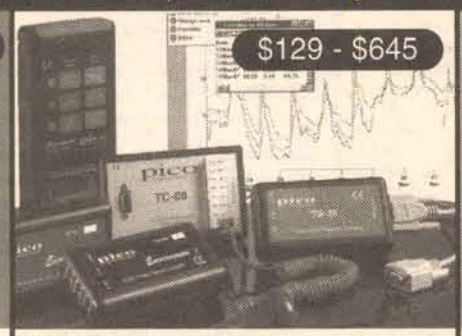

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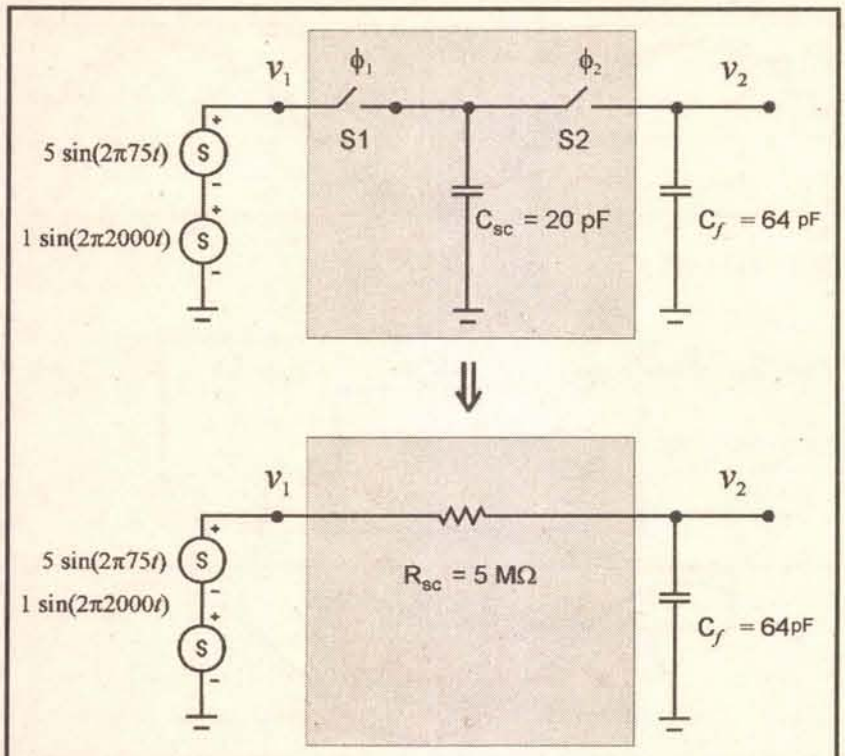

Figure 3. Equivalent of circuit shown in Figure 1.

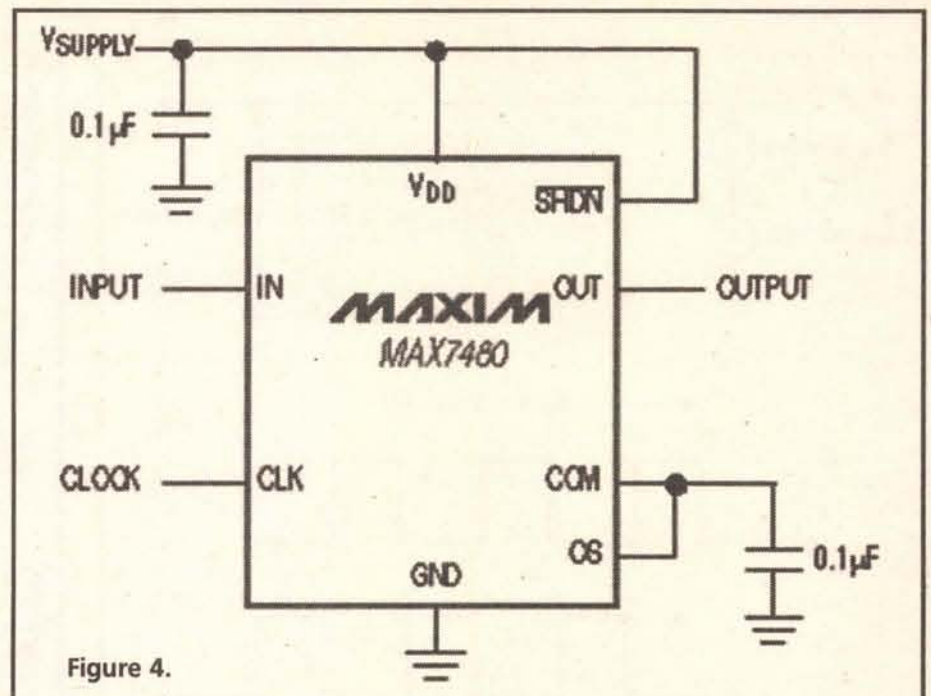

Figure 4.

A switched-capacitor filter using a MAX7480 IC and two non-critical decoupling capacitors. The external clock determines the corner frequency of this eighth order lowpass Butterworth filter according to $f_{clk}/100$.

PART	MANUFACTURER	COMMENTS
MF10	National	Two independent, universal filters. Each can be used to implement first and second order filters. The filters can be cascaded to form third and fourth order sections. Any of the classical filters (Butterworth, Bessel, Cauer, and Chebyshev) can be implemented.
LMF100	National	Pin-compatible with MF10, but offers better performance.
MF4	National	Fourth order lowpass Butterworth filter. Has on-board clock that is set with an external resistor and capacitor or accepts an external clock.
TLC04	Texas Instruments	Texas Instruments' implementation of the MF4.
MAX7480	Maxim	Eighth order, lowpass, Butterworth filter.
MAX263/264 MAX267/268	Maxim	Independent center frequency and Q selectable via input pins. Filter design software available.
MAX291/292	Maxim	Eighth order lowpass filters with on-board or external clock. Frequency range 0.1 Hz-25 kHz.
MAX295/296	Maxim	Same as above, but frequency range is 0.1 Hz-50 kHz
MAX260/261/262	Maxim	Dual, universal, microprocessor-controllable filter with more features than most people will ever need. Filter design software available.

TABLE 1

from 1 Hz to 2 kHz. The corner frequency is $f_{clk}/100$, so to implement a 500 Hz filter, the clock frequency needs to be 100 x 500 = 5 kHz. A sample circuit is shown in Figure 4.

It is also possible to run the filter without an external clock by connecting an external capacitor COSC between the CLK pin and ground. It is hard to imagine a simpler filter implementation than this. The price seems right too – the MAX7480 costs less than $2.50.

If one of the dedicated switched-capacitor filters does not meet one's needs, then a custom design using a universal switched-capacitor filter is called for. One can generally implement any of the popular filter types using standard analog filter techniques. The manufacturers have application notes, and in some instances, software available to ease the design process.

Conclusion

While most people familiar with the different kinds of filters: active/passive, Butterworth, Chebyshev, and so on, a surprising number of people are unaware of switched-capacitor filters, even though they have been around for years. This is really a shame, since these are ingenious designs, easy to work with, and very cost-effective. **NV**

References

"Introducing the MF-10: A Versatile Monolithic Active Filter Building Block." **National Semiconductor http://www.national.com/an/AN/AN-307.pdf AN-307.**

"A Basic Introduction to Filters – Active, Passive, and Switched-Capacitor." **National Semiconductor. http://www.national.com/an/AN/AN-779.pdf AN-779.**

"Programmable Universal Filter Implements C-Message Weighting Function." **Maxim Semiconductor Design Showcase http://www.maxim-ic.com/**

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